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Hamstring Tendons as Autograft Replacements in ACL Reconstructions: A Review of the Literature

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HAMSTRING TENDONS AS AUTOGRAFT REPLACEMENTS IN ACL RECONSTRUCTIONS: A REVIEW OF THE LITERATURE

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This Independent Study, submitted by Jason Anderson in partial fulfillment of the requirements for the Degree of Master of Physical Therapy from the University of North Dakota, has been read by the Faculty Preceptor, Advisor, and Chairperson of Physical Therapy under whom the work has been done and is hereby approved.

(Faculty Preceptor)

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Title	Hamstring Tendons as Autologous Replacements in ACL Reconstructions: A Review of the Literature
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ABSTRACT

Hamstring tendons have gained a great deal of acceptance in anterior cruciate ligament (ACL) reconstruction procedures in the 1990's, but some misconceptions concerning the ability of hamstring grafts to successfully replace ruptured ACLs still exist. More surgeons are using hamstring tendons to reconstruct ACL-deficient knees because their harvest does not disrupt the extensor mechanism of the knee. Enthusiasts of the hamstring graft believe that it promotes quicker return of quadriceps strength and knee range of motion without a prevalence of postoperative patellofemoral symptoms.

The purpose of this review is to dispute the concerns that exist concerning the initial tensile strength, graft site morbidity, graft fixation, postoperative rehabilitation, and long-term results of ACL reconstruction using autologous hamstring tendons. Research is presented to refute these concerns and justify the use of hamstring tendons as autologous ACL substitutes in ACL-deficient knees. Hamstring tendons have shown that they can replace the normal ACL and provide equal or better long-term results when compared to the commonly used bone-patellar tendon-bone graft.

CHAPTER I

INTRODUCTION

The most common serious ligamentous injury to the knee joint is a torn anterior cruciate ligament (ACL).[1] Incidence of ACL injuries in the general population has been estimated at one in 3000, but competitive athletes in sports such as football, skiing, and soccer have an even higher rate of injury.[2] Several factors are responsible for the increase in ACL ruptures.[3] Society's emphasis on physical fitness and general exercise has increased participation in recreational activities that place the ACL at risk. The popularity of downhill skiing, which places large stresses on the ACL, has increased a great deal in the last couple of decades. The general population is more aware of athletic injuries due to increasing media attention that is given to college and professional athletes. Heightened awareness by both patients and physicians has given rise to an increase in the prevalence of ACL reconstruction surgeries.

Approximately two-thirds of all ACL injuries are a result of non-contact situations such as hyperextension or twisting of the knee.[1] Patients often describe hearing or feeling a "pop" in the knee joint that is associated with acute swelling, pain, and instability. Clinically, ACL-deficient knees are characterized by positive anterior drawer, Lachman, and pivot-shift tests. The amount of impairment to the injured patient is determined by his or her functional demands, the degree of instability, and the level of involvement of associated structures in the knee such as collateral ligaments, menisci, the posterior cruciate ligament, and the muscular stabilizers of the knee.[4] Symptomatic instability during activities of daily living or athletics, functional impairment in persons that are unwilling or unable to change their way of life, and failure of conservative management are three indicators for ACL reconstruction. Anterior cruciate ligament reconstruction for the sole reason of preventing future osteoarthritis is not a recommended procedure. The success of ACL reconstructions is dependent upon factors such as graft selection, graft placement, healing potential of the patient, postoperative rehabilitation, and patient compliance.

The focus of this paper is the second most common autogenous ACL graft substitute, the medial hamstring complex, which is increasing in popularity because it does not disrupt the extensor mechanism of the knee and it is associated with less anterior knee pain than the autogenous bone-patellar tendon-bone (BPTB) procedure. The BPTB graft is the most popular ACL graft used in the 1990's.[1] It produces 85-90% good or excellent results and is considered the "gold standard" in ACL reconstruction. The problem with ACL reconstruction surgery has been that the BPTB graft has been used indiscriminately to reconstruct ACL-deficient knees. Some patients could be more ideally treated with the hamstring graft, but many surgeons have refused to implement the hamstring graft as a reconstructive option for ACL-deficient knees due to misconceptions regarding the mechanical properties of the hamstring graft.

The purpose of this review is to dispute the concerns that exist concerning the initial tensile strength, graft fixation, postoperative rehabilitation, and long-term

results of ACL reconstruction using autologous hamstring tendons. I do not suggest that the hamstring graft replace the patellar tendon graft, but I promote its acceptance as a viable ACL substitute. This paper is significant to physical therapists, whom are usually responsible for the rehabilitation of patients that have had ACL reconstructions, because more surgeons will become proficient in using the hamstring tendons to reconstruct ACL-deficient knees as the graft increases in popularity. It may decrease the negative bias towards hamstring grafts and benefit physical therapists in rehabilitating patients that have had ACL reconstructions using hamstring grafts.

CHAPTER II

ANATOMY AND BIOMECHANICS

The following chapter is a brief review of the anatomy and biomechanics of the knee joint along with a more critical review of the anatomy and biomechanics of the ACL. In the ongoing search to replace the ACL, the best replacement will, no doubt, be the graft that best mimics its anatomic and biologic nature.

Knee

The knee is a modified hinge joint, and due to its location at the end of two long lever arms, the tibia and femur, the knee is susceptible to excessive torsional forces and successive injuries.[5] The anatomy of the knee joint consists of three joints including the tibiofemoral joint, which is the largest joint in the body, the patellofemoral joint, and the superior tibiofibular joint. This review will focus on the tibiofemoral joint as it applies to ACL structure and function.

The tibiofemoral joint has bony involvement from the femur, tibia, and patella.[6] The articular surfaces are incongruent and consist of the convex femoral condyles, the concave tibial plateaus, and the facets of the patella. In addition to these bony structures, the knee joint relies primarily upon muscular and ligamentous supports.

An often overlooked structure in the function of the knee are the cartilaginous accessory articular structures called menisci.[7] Menisci serve a vital role in the maintenance of the knee joint as a whole. The medial and lateral menisci are fibrocartilage discs that rest in the tibial plateaus and form the concavities that the femoral condyles sit in. The medial meniscus is larger and has a semicircular shape, and the lateral meniscus is almost a full circular shape, though smaller in surface area than its counterpart. Menisci lubricate and provide nutrition to the joint structures through synovial fluid production, and they also play an important role in shock absorption and force distribution at the knee.

The menisci are very significant in the maintenance of the tibiofemoral joint, but their specific attachments and biomechanical influences are the reason for their inclusion in this review.[6,7] The menisci have common attachments to the intercondylar tubercles of the tibia, the tibial condyles via the coronary ligaments, and to the patella. The lateral meniscus, which is relatively loosely connected as compared to the medial meniscal connections, has unique attachments to the ACL, posterior cruciate ligament (PCL), and the popliteus muscle. The medial meniscus has its unique connections to the medial collateral ligament (MCL) and semimembranosus muscle.

As a result of the medial meniscus' firmer attachment to the tibial condyle, it has much less mobility than the lateral meniscus.[7] This decrease in mobility is a possible reason for its increased frequency of involvement in knee injuries as compared to the more mobile lateral meniscus. The medial meniscus is commonly torn along with the ACL and MCL in traumatic knee injuries. This injury is popularly referred to as the "terrible triad" or the "triad of O'Donahue."

Even though the menisci enhance tibiofemoral joint congruity, the knee joint is still a relatively incongruent joint that is predisposed to mechanical weakness.[7] The joint relies heavily on muscular and ligamentous support structures for its dynamic and static stability. The primary muscular stabilizers of the knee are the quadriceps and hamstrings. They function together to control knee flexion angle in everyday activities like stair climbing, rising from a chair, and squatting.

The quadriceps femoris is a group of four muscles that are known as the extensors of the knee.[6,7] This group consists of the vastus lateralis, vastus intermedius, vastus medialis, and the rectus femoris. They have a common insertion as their fibers unite to form the quadriceps tendon before it inserts into the superior aspect of the patella. In order for the quadriceps to function as knee extensors, the quadriceps tendon continues distally as the patellar ligament before finally inserting on the tibial tuberosity. The quadriceps function together to extend the knee via their insertion on the tibia.

As the quadriceps extend the knee, they provide a force that causes an anterior translation of the tibia in relation to the femur as well.[7] This anterior motion of the tibia is checked by the ACL, which is the primary non-contractile restraint of anterior translation of the tibia. Active quadriceps contraction places stress on the ACL, but the ACL is not alone in limiting anterior motion of the tibia on the femur.

The hamstring muscles, which all originate from the ischial tuberosity, aid the ACL in its effort to limit anterior subluxation of the tibia.[6,7,8] This group consists of the semitendinosus, semimembranosus, and the biceps femoris muscles. The semitendinosus and semimembranosus insert on the anteromedial and posteromedial aspect of the tibia, respectively. The biceps femoris inserts onto the lateral condyle of the tibia and the head of the fibula. The tendon of the gracilis muscle, which is often used in hamstring grafts, originates on the inferior ramus of the pubis and inserts with the semitendinosus on the medial proximal tibia. More et al[8] have concluded that the hamstrings are a synergist to the ACL. They completed a study using cadavers that assessed the role of the hamstrings during a simulated squat exercise. The squat was performed with different loads applied to the hamstring tendons and with the hamstring tendons excised. Adding hamstring tension significantly decreased the amount of anterior tibial translation without any measurable effect on quadriceps force. The hamstrings function synergistically with the ACL to provide anterior stability to the knee.

Non-contractile stabilization of the knee comes from the joint capsule and the peri-ligamentous structures including: MCL, lateral collateral ligament (LCL), ACL, and PCL.[6,7] It would require a separate review to do justice to the complex pattern of stability and mobility that occurs at the knee, so only a brief mention of the accessory restraints in the knee has been included. The ACL is crucial to the stability of the knee and has been focused on in the entirety of this chapter.

Anterior Cruciate Ligament

The ACL is considered the primary stabilizer of the knee.[2,9,10] It arises from the posteromedial aspect of the lateral femoral condyle and descends in an anteromedial direction to its distal attachment on the anterior aspect of the intercondylar area of the tibia. Cross-sectional area of the ACL at its tibial attachment is approximately two times the area of its mid-substance, and the average length of an ACL is 31-38 millimeters. The ACL is not a singular cord, but rather a collection of individual fascicles that fan out as they reach their tibial insertion. A lateral spiraling of the ACL occurs as it descends to its tibial attachment producing a twist in itself. This twisting adds to the complex structure of the ACL and certainly is related to its role in guiding the gliding and rolling of the knee throughout knee range of motion.

Researchers generally agree that the microstructure of the ACL mimics the hierarchical organization of tendons.[11,12] Individual fibrils are grouped into fibers which make up subfascicular units and finally are aggregated into fasciculi. All fasciculi together form the ligament as a whole. These fibrils, fibers, and fasciculi are bound by loose connective tissue termed endotenon and epitenon, respectively. The entire ligament is covered by a similar type of loose connective tissue called paratenon.

Fascicles are organized into bundles that twist upon themselves as they descend to their tibial insertion and give the appearance of two distinctive bands.[2,9,10] Current research by Mommersteeg et al[13] contradicts this theory that their are two anatomically distinct bundles of the ACL. They conducted an experiment to try to define the spatial orientation of the fascicles at their tibial and femoral insertion sites. Using a three-dimensional digitiser, it was concluded that fiber bundles that were at one time neighbors did not always remain neighbors. A changing relationship of the fiber bundles from the femoral to tibial insertion sites was noticed. Mommersteeg supports a theory of functional arrangement of fascicles and disagrees with previous researchers that have found two or three anatomically distinct bundles.

Investigators doubt the bundle theory of fascicular organization, but it is still the popular belief that the ACL has two anatomically distinct bands of fascicles.[2,9,11-13] The bands are named the anteromedial and the posterolateral bands with respect to their tibial attachments. The posterolateral band is considerably larger than the anteromedial band and is tight in knee extension and relatively lax in flexion, while the anteromedial band is taut in flexion and relatively lax in extension.

Although the theory of separate bands provides some basic information about the dynamics of the ACL, its function is much more complicated.[10] The fact that each fiber of the ACL is of a different length and has a unique femoral and tibial attachment is a prime reason that surgeons have not been able to master its reconstruction. There is a continuum of tension between the fascicles of the normal ACL. The ACL's complex fascicular nature allows a portion of it to be taut at all times with no change in length throughout knee range of motion. This characteristic means that the ACL functions isometrically as it supports the knee joint.

In addition to its role as the primary restrainer of anterior tibial translation and posterior femoral translation, the ACL also plays a secondary role in restraining rotation and varus forces at the knee.[7,14] This is evident when one considers the most common mechanism of injury of the ACL, which is a combination of knee flexion and rotation. Flexion and medial rotation stress the ACL as it wraps around the PCL in an attempt to restrict this motion. Flexion and lateral rotation stress the ACL, though much less than internal rotation, as the ACL is stretched across the surface of the lateral femoral condyle. The ACL is a primary restraint of anterior tibial translation, a primary-secondary restraint of internal tibial rotation, and a secondary-secondary restraint of varus, valgus, and external tibial rotation.

Neurovascular Structure of the ACL

The synovial lining of the ACL is abundant with vessels that originate from the middle genicular artery, and a lesser amount from the lateral and inferior genicular branches.[15-17] The vessels that run longitudinally within the infrastructure of the ACL arise mainly from soft tissues such as the infrapatellar fat pad and this synovium. Vessels in the synovium form a web of vasculature around the ACL, and then penetrate in a transverse orientation before joining with smaller vessels that traverse the length of the ligament. The vasculature of the ACL is not derived from osseous attachments, but largely from its peri-ligamentous soft tissue structures.

The tibial nerve is the origin of the neural component of the ACL.[18] Its fibers originate posteriorly and accompany the vessels of the synovium as they penetrate the ACL. These neural branches are thought to be the afferent avenues for mechanoreceptors that are located in the ACL. Sensory organs, such as golgi tendon organs, ruffini and pacinian corpuscles, and free nerve endings have been identified upon histologic examination of the ACL.[19] Only 1% of the volume of the ACL has been attributed to free nerve endings, which are responsible for sensation of pain. This may explain why injuries to the ACL are associated with a popping sensation and instability, but severe pain is not always felt at the time of rupture.[18] The ACL plays a major role in position sense and articular motion at the knee, but it is rather limited in perceiving pain.

The role that the ACL plays in sensorimotor and proprioceptive function in the knee is debatable, but it is an area of burgeoning research.[20] Due to the extensive histological findings concerning afferent and efferent structures of the ACL, it is assumed that the ACL has a significant role in sensory function of the knee. Research on the role of the ACL in sensorimotor function is ambiguous, but most studies have documented an effect of joint afferents on skeletal motoneurons. Loading the ACL has shown facilitation of the hamstrings and inhibition of the quadriceps in cats, but opposite results have been noted by another researcher using a similar protocol.[21,22] Johansson[23] has demonstrated that the ACL has an effect on the gamma motor system in cats by applying tension loads of 500 to 2000 grams to the ACL. The tensile loads altered the discharge response patterns of muscle spindles in stretched knee flexors indicating that afferent input from the ACL had an effect on the hamstrings in cats.

Proprioception and its relation to the ACL is also a debatable and often-researched question.[20] Proprioception is the ability of the nervous system to sense position and motion of body segments at both conscious and unconscious levels. A recent study has shown that the detection of movement and the ability to reproduce static position are deficient in cruciate-injured individuals two to 14 years after injury.[24]

Muscles that cross the knee joint provide a significant amount of stability to the knee. Since the ACL does seem to affect muscles about the knee via its afferent structures, its loss could, and does, lead to decreased joint stability.[20] Altered muscle recruitment after cruciate injury combined with the resultant instability could lead to osteoarthritis. It is difficult to determine if the altered muscle firing patterns following ACL ruptures are due to the primary loss of ACL afferents or to periarticular structures that fire as a result of abnormal subluxations. Although the ACL's role in sensory function is not clearly defined at present, proprioception loss does occur and needs to be addressed in prospective surgical procedures and postoperative rehabilitation programs.

CHAPTER III

HISTORY OF ACL RECONSTRUCTION SURGERY

Anterior cruciate ligament injury has become familiar to the general public in recent years, but this type of injury has been occurring for hundreds of years. Surgery has become a very popular treatment over the years in order to return patients to work or play. The goal of surgery and rehabilitation is to prevent recurrent injury while allowing people with ACL-deficient knees to return to work and activity levels that they choose.

As previously noted, the menisci are shock absorbers and force distributors in the knee.[7] They are vital to the maintenance and function of the normal knee, but the menisci do not play a significant role in stability in the normal knee. The inherent instability that results from an ACL injury alters the role of the menisci.[25] The menisci continue to distribute the load at the knee and protect the articular surfaces, but they also assume a more demanding role in knee stability in the absence of the ACL. Menisci must distribute larger forces in an ACL-deficient knee. Any change in their structure alters their ability to function and leads to progressive damage of the articular surfaces. An ACL disruption left untreated leads, almost invariably, to subluxations of the knee and meniscal injuries which ultimately lead to joint arthrosis.[26] The intent of the first surgical repair of the ACL was probably not to prevent meniscal damage and arthritis, but rather to restore function.

The first reports of ACL disruptions and their clinical implications came in 1836 by the Weber brothers.[27] Clinical symptoms of ACL ruptures were first described by Bonnet in 1845.[28] He noted an audible snap at the time of injury, haemarthrosis, and altered knee joint mechanics. It was not until 1895 that the ACL was surgically repaired, though. Mayo Robson performed the first ACL repair and Battle followed him with a repair in 1898.[27] Interest in the ACL increased rapidly throughout the 1900's and many different surgeries were attempted to correct the resultant instability.

The earliest structures used to replace the ACL were static, or fixed.[27] Silk structures were combined with the semitendinosus tendons to be the first prosthetic replacement used to stabilize the knee by Lange and Herz in 1903 and 1906, respectively. Two loops of silver wire, one passing through the lateral femoral condyle and one through the tibia, were used to form a new ACL by Corner in 1914. These prosthetics along with nylon, Dacron, polytetrafluoroethylene, polyethylene, polypropylene, carbon fiber, and polyester have all been used without success as ACL substitutes. A kangaroo tendon was used in 1933 by Bircher as the first xenograft to replace the ACL. An explosion of interest in the repair and replacement of the ACL in the early 1900's led surgeons to many creative, yet unsuccessful, procedures. In 1996, Dandy[27(p 257)] said, "No ligament prosthesis or synthetic replacement developed so far has been satisfactory in the long term."

The earliest formal reports of autogenous replacement of the ACL were by E.W. Hey Groves in 1917.[27] He passed a proximal strip of the iliotibial band through the femur and tibia and sewed it to the periosteum of the tibial crest. Several closely related procedures were used throughout the 1920's using fascia lata strips to mimic the ACL with mixed results. The first reports of the patellar ligament as a graft material were noted in 1933 by Zur Verth, and the semitendinosus was first used by Macey in 1939.

In 1963, Kenneth Jones[29] used the central third of the patellar ligament to replace the deficient ACL. The graft was always too short because he left the distal attachment in place. Jones attached the graft via its patellar bone plug in a position anterior to the intercondylar notch, which is far from its natural attachment. The results from this procedure were poor, but its implications have been vast.[27] Many North American surgeons were influenced by Jones, and his name is often associated with patellar tendon procedures that are in use today even though these procedures are vastly different in that they are based upon a free patellar tendon graft. The current intra-articular procedure using the central third patellar tendon to replace the ACL got its roots from this unsuccessful attempt by Jones in 1963, and is generally considered the "gold standard" in ACL reconstruction.

Evolution of the Semitendinosus/Gracilis Tendon ACL Reconstruction

Like the patellar tendon procedure, the use of hamstring tendons as ACL replacements has undergone much evolution since its inception in 1939.[30] Macey,[31] in 1939, left the semitendinosus attached to the tibia and routed it through tibial and femoral tunnels before attaching it to bone periosteum with the knee in full extension. Most hamstring procedures performed today are variations of Macey's initial attempt to replace the ACL.[30] A proximally based gracilis tendon was routed through the posterior capsule and attached to the intercondylar notch in a dynamic attempt to substitute for the ACL.[27] Leaving the graft attached to its proximal muscle belly was hypothesized to prevent the graft from stretching out and provide superior proprioception compared to the free, denervated grafts. Respectable results were reported, but sample sizes were very small and few objective measures were documented. These dynamic ACL reconstructions are extinct today in favor of more effective methods.

Puddu[32] modified the distally based techniques of Macey. He routed the semitendinosus tendon with a piece of bone from its tibial insertion through a medial tibial drill hole. The graft was fixated by a suture to the iliotibial band. The musculotendinous unit was left intact proximally and its flexion and internal rotation ability was preserved. He reported results on twelve patients with chronic anteromedial and anterolateral instability. All patients regained normal ROM and had less than 1+ anterior drawer. This procedure was repeated by many surgeons in combination with the gracilis tendon, or an extraarticular procedure in acute and chronic knees. Barber et al[33] compared Puddu's technique using semitendinosus and gracilis tendons in acute and chronic ACL patients in 1991. Eighty-one percent of acute reconstructions and 76% of the chronic laxity patients were classified as excellent or good after 52 months. The pivot-shift was completely eliminated in all acute patients, but it was negated in only seventy-one percent of the chronic group. This procedure proved to be a viable technique in acutely injured patients at that time, but it was not effective in chronically unstable patients.

Biomechanical data in a preliminary report by Noyes stated that the semitendinosus is only 50% the strength of the normal ACL and provoked much change in the hamstring grafts.[30] Lipscomb,[34] in response to the aforementioned biomechanical data, used a single-stranded semitendinosus and gracilis graft. Of 342 patients, good results were reported in

84% at an average of 22 months. Others attempted using a double-looped semitendinosus tendon to counteract its innate biomechanical weakness as compared to the patellar tendon.[30] Mott,[35] in 1983, was the first to use a double-looped semitendinosus free graft, but no results were reported. Mott and other surgeons were trying to create a graft that better approximated the tensile strength of the normal ACL. Gomes and Marczky[36] reported good results in 23 of 26 patients after three years with a double-looped semitendinosus free graft. Zaricnznyj[37] used a double-looped semitendinosus and gracilis free graft and reported excellent or good results in 85% of chronically deficient patients. These studies were completed using small sample groups, but they did stimulate optimism for free hamstring grafts as an autogenous ACL substitute.[30,38]

These results using the double-looped semitendinosus grafts were encouraging, but in 1986 Moyer et al[39] introduced the use of an arthroscope in ACL reconstructions using hamstring tendons. He used a single-limbed semitendinosus and gracilis graft that was harvested from the proximal thigh rather than disrupting the more fragile distal insertions of the flexor tendons. With the assistance of an arthroscope, a steinman pin was used to locate the anatomic insertion sites of the original ACL. Bone tunnels were drilled with a cannulated drill and the tendons were passed across the joint. This method decreased post-op pain, quickened muscle recovery, and decreased patellofemoral symptoms as compared to the non-arthroscopic, open procedure.[38] All current ACL reconstructions are arthroscopically-assisted procedures because the morbidity associated with this technique is drastically improved as compared to the open techniques of the past.

Since the advent of the arthroscopically-assisted reconstructions, many techniques have been designed using hamstring tendon grafts to replace the ACL.[30] Many combinations of hamstring tendons have been used in attempts to increase initial tensile strength and improve graft fixation strength. Popularity of the graft among surgeons has been hindered by the poor results of the early single-stranded and poorly fixated grafts. Today, the hamstring grafts of choice are the double-looped semitendinosus and gracilis autograft and the four-stranded semitendinosus graft. The remainder of this paper will focus on decreasing skepticism towards the use and rehabilitation of hamstring grafts in ACL reconstructions.

CHAPTER IV

GENERAL HAMSTRING GRAFT CONCERNS

There are many concerns about the use of hamstring tendons as autograft replacements for the ACL. The BPTB autograft is currently the "gold standard" in ACL reconstruction, and much of the reason for its prevalence in ACL reconstructions is based on the research of Noyes et al.[40] (See Table 1.) Noyes subjected ligament graft tissues to high strain-rate failure tests to determine their tensile strength and stiffness. The substitute grafts were compared to the mechanical properties of ACLs from a similar sample of young donors. He found that the central one-third patellar tendon was the strongest of the ACL replacement grafts with a mean strength of 168% of normal ACLs.

Table 1. Results of Biomechanical Testing Concerning Strength and Stiffness of Anterior Cruciate Ligaments and Their Replacement Tissues. (Modified from Noyes.[40])

Tested Tissues	Maximum Load(N)	Stiffness(KN/m)
ACL (n=6)	1725 +/- 269	182 +/- 33
Central 1/3 BPTB (n=7)	2900 +/- 260	685 +/- 85
Semitendinosus (n=11)	1216 +/- 50	186 +/- 9
Gracilis (n=17)	838 +/- 30	171 +/- 11
Distal Iliotibial Tract (n=10)	769 +/- 99	not determined
Fascia Lata (n=18)	628 +/- 35	118 +/- 5

The semitendinosus and gracilis (STG) tendons were 70% and 49% as mechanically strong as an ACL, respectively.[40] Distal iliotibial tract, fascia lata, and patellar retinacular fibers were 44%, 36%, and 20% as strong as an ACL. The STG tendons and BPTB grafts are the primary autograft substitutes used in ACL reconstructions largely due to Noyes' results.

Noyes[40] also determined the stiffness of the patellar tendon, semitendinosus, gracilis, distal iliotibial tract, fascia lata, and patellar retinacular fibers. (See Table 1.) Once again, the BPTB graft had the largest stiffness rating of any of the grafts including the standard ACL. The normal ACL had a stiffness of 182 KN/m, but the BPTB graft had a stiffness (685 KN/m) close to four times that of the ACL. STG tendons had stiffness values of 186 KN/m and 171 KN/m, respectively. These values for the hamstring tendons are virtually identical to the stiffness of the ACL.

Noyes[40] was a pioneer in investigating tensile strength of ACL substitutes and was instrumental in advancing the research on ACL replacement tissues. Hamstring graft enthusiasts were not disappointed in the results of this study, though. Sitter and Grana of the Oklahoma Center for Athletes examined the strength and stiffness of double-looped STG grafts.[30] They found that the hamstring grafts nearly doubled in tensile strength and stiffness as compared to Noyes'[40] study. This should come as no surprise, since Noyes has suggested that graft strength can be increased by increasing cross-sectional area of the tissue source. As long as each arm of the graft is tensioned equally, a doubled STG graft would have an estimated tensile strength of 250% (4108 N) of a normal ACL according to Noyes original values.

A study by Howell and Taylor[41] explained the advantages of a double-looped hamstring graft compared to the BPTB graft in terms of cross-sectional area. A normal

ACL is an average of five millimeters (mm) thick and 10 mm wide with a cross-sectional area of 50 square mm.[42] The average width of the double-looped hamstring graft is eight mm, which provides a circular graft of 50 square mm that more closely resembles the original ACL.[41] A patellar ligament is a rectangular structure that is 10 mm wide with a cross-sectional area of 35 to 40 square mm. The cross-sectional area of the four-stranded hamstring graft more closely approximates the area of a normal ACL.[41] Howell and Taylor[41] also believe that their four-stranded hamstring graft has more tensile strength than the 10 mm-wide patellar ligament. Noyes'[40] data was extrapolated to conclude that the tensile strength of a double-looped STG graft and a 10 mm-wide patellar ligament would be 238% and 138% of the strength of an ACL, respectively. These numbers are not results of experimental research and are based on theoretical principles.

The shape of these two grafts is the reason the hamstring graft has a larger cross-sectional area than a patellar ligament of the same width.[41] A 10 mm-wide patellar ligament that is four mm thick has a cross-sectional area of 40 square mm. An eight mm-wide hamstring graft has a cross-sectional area of 50 square mm due to its cylindrical shape. It would take a 12 mm-wide patellar ligament to provide equal cross-sectional area to a eight mm-wide hamstring graft. Double-looped hamstring grafts approximate the cross-sectional area of a normal ACL, and STG grafts have a greater margin of strength than the patellar ligament making it an excellent option to consider in ACL reconstructions.

Hamstring Graft Site Morbidity

Several studies have suggested that hamstring tendon grafts are associated with fewer donor site complications when compared to BPTB grafts.[30,43,44] Sachs et al[45] reported significantly more incidences of patellofemoral pain and greater quadriceps weakness with BPTB grafts as compared with STG grafts. Brown et al[30] reported no quadriceps deficit between the two autogenous grafts after one to two years, but he did report a difference at six months. Normal quadriceps strength was achieved in these patients with hamstring grafts in three to six months, but at six months most recreational athletes having had a BPTB procedure only had an 80% return of quadriceps strength. Wilk[46] conducted a study on recreational athletes in an accelerated rehabilitation program and demonstrated that isokinetic quadriceps strength was 20-25 % reduced six months following a BPTB ACL reconstruction. Quadriceps strength is regained faster and easier in patients that undergo ACL reconstructions using the hamstring tendons versus BPTB reconstructions.

A major concern about the use of hamstring tendons for ACL reconstructions is the possibility of residual hamstring strength deficit.[30] Lipscomb[47] assessed hamstring strength via isokinetic testing a 26.2 months after STG ACL reconstruction. Fifty-seven patients were tested at 60 and 240 degrees per second and they displayed hamstring strength values of 98% and 100% as compared to the opposite extremity, respectively. There was not a significant hamstring strength deficit following harvest of hamstring tendons for

ACL reconstruction. Aglietti[44] also demonstrated no significant loss of flexor strength in a random study of 30 BPTB and 30 four-stranded STG reconstructions. After an average of 28 months, the knee flexor strength was 94%, 95.7%, and 91.6% at 60, 120, and 180 degrees per second, respectively. Karlson[48] reported full return of hamstring strength at 60 degrees per second in a group of 64 patients that underwent a two-stranded STG ACL reconstruction. These studies demonstrate that hamstring strength deficit following ACL reconstruction using the semitendinosus and gracilis is not a serious problem.[44,47,48]

A study by Yasuda et al[49] evaluated quadriceps and hamstring strength morbidity associated with harvesting of the hamstring tendons compared to the morbidity that occurs due to harvesting and reconstruction. (See Table 2.)

Table 2. Relative Isometric Strength of the Hamstring Muscles$^{@}$ (Modified from Yasuda.[49])

Group	Preoperative Period	Postoperative Period (Months)				
		1	3	6	9	12
R-H-	100	106	138	128	128	120
R-H+	100	72$^{\#}$	105$^{\#}$	108$^{\#}$	108$^{\#}$	104
R+H-	88	63	93	100	108	111
R+H+	80	43*	82	90	98	101

$^{@}$ Strength measured at each period represented as a ratio (%) of the reference
$^{\#}$ P< .05 (R-H- vs. R-H+)
* P< .05 (R+H- vs. R+H+)

They conducted a randomized study of 65 competitive and recreational athletes. The patients had an ACL reconstruction done using either the contralateral or ipsilateral hamstring tendons. Torque was measured in the non-operated knee for each muscle using a Cybex II dynamometer during the preoperative evaluation. Isokinetic values were determined at 60 degrees per second in pre and postoperative situations. (See Table 3.)

Table 3. Relative Isokinetic Peak Torque of the Hamstring Muscles at 60 deg/sec (Modified from Yasuda.[49])

Group	Preoperative Period	12 Months Postoperative
R-H-	100	122
R-H+	100	99
R+H-	91	99
R+H+	88	99

The torque values measured at each postoperative evaluation were a ratio of the preoperative uninjured musculature. The knees were divided into four groups based on graft harvest and reconstructive surgery. Patients in the ipsilateral group had a knee without any surgery (R-H-) and a knee with both harvest and reconstruction (R+H+). Patients in the contralateral group had a knee with harvest only (R-H+) and a knee with reconstruction only (R+H-).

To isolate morbidity associated with hamstring tendon harvest they compared knees that only had tendon harvest R-H+ to knees that had no surgeries R-H- performed.[49] Non-operated knees increased quadriceps and hamstring isokinetic and isometric strength to 120% of the preoperative value by 12 months. Average isometric quadriceps strength in knees that only experienced harvest increased to at least 120% of the reference value by three months postoperatively. Average isometric hamstring strength reached 105% of the reference value by three months in the R-H+ group. The R-H+ group had isokinetic strength values of 110% and 99% at 12 months. Quadriceps strength was not reduced by hamstring tendon harvest using this rehabilitation program, and isometric hamstring strength was returned to 105% of the uninjured knee flexors in only three months. These results demonstrate that isolated hamstring tendon graft site morbidity is very minimal.

In order to investigate morbidity caused by hamstring tendon harvest in knees with an accompanying ACL reconstruction, knees with harvest and reconstruction were compared to knees with only reconstruction.[49] Isometric quadriceps strength returned to 100% of the reference value in both groups by nine months and was at 90% by six months. Isometric hamstring strength returned to 100% and 90% at six months for the R+H- and R+H+ groups, respectively. At nine months postoperatively, isometric hamstring strength had returned to 108% and 98% in the R+H- and R+H+ groups, respectively. Isokinetic hamstring strength recovered to 99% of the reference value by 12 months in one year in both groups, but isokinetic quadriceps strength only returned to 93% and 83% at 12 months in the R+H- and R+H+ groups, respectively. A factor in the quadriceps muscles not making a full recovery in the R+H+ group may have been the lack of a preoperative quadriceps strengthening program. BPTB enthusiasts have cited a residual hamstring deficit as a major drawback to using the hamstring tendons as autologous replacements for the ACL, but several studies have not shown a residual hamstring strength deficit.[44,47-49] Hamstring tendons can be used as an autologous ACL replacement without causing a residual hamstring strength deficit.

Graft Fixation

The weakest link of the ACL graft during the early stages of rehabilitation is dependent upon the method of fixation.[3] Interference screws are the standard technique used to secure BPTB grafts, but there is no agreement among surgeons as to the ideal hamstring graft fixation technique. Surgical methods for graft fixation include staples, sutures over endobuttons, sutures over post screws, interference screws, and screws with spiked, soft tissue washers.[4] Many of the early hamstring graft fixation techniques have become extinct as the hamstring graft has evolved in recent years.[50]

Classically, the patellar tendon reconstruction procedure has been used due mostly to its strong initial fixation strength using bone-to-bone interference screw fixation.[30] Jomha et al[51] reported values of 455-621 newtons (N) depending on the angle of screw insertion. Kurosaka[52] conducted BPTB surgery on cadavers and obtained strength and stiffness values of 476 +/- 111 N and 58 +/- N/mm. Advocates of the BPTB procedure have doubted the fixation strength of hamstring tendon grafts. New materials and methods of fixation have made hamstring grafts just as reliable as interference screw fixation in BPTB grafts.[30] Adequate initial fixation strength is crucial in order to allow for early postoperative motion and weight bearing. Most activities of daily living load the ACL to appoximately 450 N (100 lbs.) of force or less, so graft fixation strength needs to exceed this value to endure rehabilitation.[40]

Several fixation methods of hamstring grafts and patellar tendon grafts were studied by Steiner et al.[53] (See Table 4.) Four different techniques were used to assess fixation strength and stiffness of hamstring and BPTB autografts.

1. STG_{sut}-(2 limb) Semitendinosus and gracilis tendons (STG) were taken as free grafts and not doubled. A suture (sut) was placed through the end of each tendon using a whip stitch. The four suture strands were tied to either a tibial or femoral post screw and washer.

Table 4. Tensile Properties of the Normal ACL and Graft Fixation Complexes. (Modified from Steiner et al.[53])

Structure	Maximum Load (N)	Stiffness (N/mm)
ACL	800	66
STG_{sut}	335	16
$DSTG_{sut}$	573	18
STG_{was}	519	20
$DSTG_{was}$	821	29
$BPTB_{int}$	423	46
$BPTB_{sut}$	396	27
$BPTB_{endo}$	588	33
$BPTB_{is\text{-}sut}$	674	50

2. $DSTG_{sut}$-(4 limb) Doubled semitendinosus and gracilis tendons (DSTG) were bisected to produce four tendon limbs of equal length. One suture was used in the gracilis ends and one suture was used in the semitendinosus ends prior to identical attachment to tibial or femoral posts as in STG_{sut}.

3. STG_{was}-(2 limb) STG free grafts (not doubled) were secured to the femur by weaving them around two spiked, soft tissue washers (was) and bicortical screws. They were secured distally by a spiked, soft tissue washer and bicortical screw.

4. $DSTG_{was}$-(4 limb) STG were doubled and looped to produce two looped ends and four free ends. The free ends were secured proximally by weaving around two spiked washers and screws like in the STG method (no sutures). Distal attachment was achieved by placing three sutures through the looped ends and tied to a post screw and metal washer.

Four fixation techniques were evaluated for BPTB grafts:

1. $BPTB_{is}$- Femoral and tibial fixation was done with interference screws (is) alone.

2. $BPTB_{sut}$- Femoral and tibial fixation was completed by placing three sutures through each bone plug and fixed to post-screws with a metal washer.

3. $BPTB_{endo}$- Femoral fixation was done by placing interference screws from the inside out using an endoscope (endo). Tibial fixation was done with sutures as in $BPTB_{sut}$.

4. $BPTB_{is\text{-}sut}$- A combination of interference screws in an outside-in manner and suture fixation as in $BPTB_{sut}$ using post-screws and metal washers.

The study by Steiner[53] was completed on cadavers with an average age of 69.5 years (range, 48-79). Preliminary testing determined that the intact ACLs tolerated 800 +/- 469 N of force prior to rupture with 66 +/- 26 N/mm of stiffness. The testing was completed using an anterior translation force with the reconstructed cadaver knee in a tensiometer. The authors chose this method because graft bending occurs at the bone tunnels and this produces a stress shielding effect on the ACL graft. This motion is also the primary force that stresses the ACL graft during rehabilitation. The strongest hamstring graft fixation method in this study was the $DSTG_{was}$ with a fixation strength of 821 +/- 219N. This value was nearly identical to the maximum load tolerated by the intact ACLs, but its stiffness value was less than 50% of the ACLs tested in this study. The washer techniques provided significantly greater maximum load and stiffness values as compared to the similar graft using suture fixation.

The patellar tendon autografts in Steiner's[53] study produced stiffness values that resembled the stiffness of the original ACLs. The use of interference screws at each end resulted in 46 N/mm to 50 N/mm of stiffness in the $BPTB_{is}$ and $BPTB_{is\text{-}sut}$ conditions. The patellar tendon procedure ($BPTB_{is\text{-}sut}$) that had the highest maximum load value (674 N) and stiffness (50 N/mm) had interference screws and sutures at both ends of the graft.

A more recent study by Rowden et al[54] evaluated hamstring and patellar tendon autograft fixation strengths using similar methods as compared to Steiner.[53] The cadavers in this study were all under 42 years of age whose death did not involve trauma to the knee. Rowden's results, unlike Steiners', were not skewed by degenerative changes due to age, sedentary lifestyle, injury, and freeze preparation. The knees were all obtained within 48 hours of death and wrapped in saline-soaked gauze.

The 20 knees were placed in three groups including a control group (9), a patellar tendon group (6), and a semitendinosus group (5).[54] In the control group, all soft tissues except the ACL were removed prior to strength and strain analyses. In the patellar tendon group, a BPTB ACL reconstruction was completed with a 10 mm-wide strip from the middle of the patellar tendon. Bone plugs of 25 mm were obtained with the graft and fixed with proximal and distal interference screws. The semitendinosus group was constructed using a quadruple-stranded graft using the Rosenberg technique. Proximal fixation was done using a titanium button (endobutton) and braided polyester tape. Distal fixation was done via braided polyester sutures tied around a post screw. Two strips of semitendinosus tendon were acquired and doubled leaving the free ends distally. A whip stitch was used in each free end using non-absorbable polyester suture leaving eight free ends of suture. The titanium buttons were attached to the looped ends using braided polyester tape. The length of the tape was calculated to allow at least 15 mm of tendon to remain in the femoral and tibial bone tunnels. The buttons were passed through the tibial and femoral drill holes before being locked in place. Then, the distal sutures were tied to a bone screw.

After dissection and reconstruction surgeries, the knees were placed at 30 degrees in a tensiometer.[54] The control group displayed strength and stiffness of 2195 +/- 427 N and 306 +/- 80 N/mm, respectively. These values are four to five times stronger and five to six times stiffer than the patellar tendon and semitendinosus groups. The patellar tendon group withstood 416 +/- 166 N of force and the semitendinosus group had an average strength of 612 +/- 73 N. The semitendinosus was significantly stronger and had less variation in strength as compared to the BPTB group. The BPTB group had 51 +/- 17 N/mm of stiffness versus the semitendinosus group which had 42 +/- 23 N/mm of stiffness. The stiffness values were not significantly different from each other.

The maximum load to failure results of Rowden's[54] study coincide with the obtained strength values of Steiner's[53] study using similar grafts. Rowden's study differs from

Steiner's in that the stiffness values for the quadrupled semitendinosus graft were not significantly different from the BPTB graft. This may be explained by the fact that Rowden's study assessed cadavers with an average age of 26.6 years versus 69.5 years in Steiner's study. Steiner was limited by the age of the cadavers and that the cadavers had been stored at -20 degrees C. Rowden demonstrated that a quadrupled semitendinosus graft with titanium button fixation could tolerate loads 50% greater than BPTB reconstructions at time zero while providing similar stiffness values.

Beynnon et al[50] compared the double staple belt buckle soft tissue technique to the spiked washer figure of eight soft tissue fixation technique. The double staple belt buckle technique fixes the graft to the distal femur with a proximal staple, and then the graft is doubled over itself before another staple is placed over the double thickness of the tendon. The figure of eight technique is similar to the $DSTG_{wash}$ technique that was used by Steiner. The double staple belt buckle method had an average ultimate failure value of 875 N. It was significantly stronger ($p<.005$) than the double screw and spiked washer figure of eight technique that had a mean ultimate strength to failure of 539 N.

There is convincing evidence that hamstring tendon grafts can be fixated with time zero strength and stiffness that is equal to or greater than BPTB autografts.[50,53,54] Earlier hamstring tendon ACL reconstruction procedures that have demonstrated inadequate results tend to be associated with a single or double stranded hamstring grafts that were fixated with a single staple rather than the more modern techniques. The double staple belt buckle method, the Rosenberg technique using the titanium endobutton, and the figure of eight method using bicortical bone screws with spiked soft tissue washers have all proved themselves capable of resisting the stresses that early rehabilitative exercises and activities of daily living place on the healing ACL graft.

Soft Tissue to Bone Healing

The histology and biomechanics of tendon to bone healing is another of the concerns with hamstring grafts since they are not harvested with bone plugs. Animal models have shown that tendon healing in bone tunnels does occur.[55] There is a progression of collagen fiber continuity between the tendon and bone that resembles Sharpey's fibers. Sharpey's fibers normally anchor tendons to bones as they make the transition to their bony insertion. These fibers gradually accrue and signify graft incorporation and maturation in ACL grafts.

Biomechanical testing has shown that the site of graft failure moves gradually from the insertion site to the mid-substance of the tissue replacement.[55] Prior to eight weeks the tendons pulled out from the bone tunnels. After the eighth week all failures occurred at the mid-substance of the tissue. Biologic incorporation of tendon to bone at fixation sites is speculated to occur between six to twelve weeks, and soft tissue-to-bone healing sites should be protected during this period. Graft fixation strength needs to be a priority in grafts with tendon-to-bone healing in order to accommodate the biologic incorporation process.

CHAPTER V

REHABILITATIVE CONCERNS OF THE HAMSTRING GRAFT

Replacement tissues used in ACL reconstructions undergo a remodeling and incorporation process after implantation.[56] This process occurs in all autologous and allograft tissues including patellar tendons. Anterior cruciate ligament reconstruction involves placing a collagenous tissue across the knee joint that is remodeled and incorporated as organized scar tissue. The substitute does not remodel to the extent that it simulates the complex microanatomy of a normal ACL, though.

Biology of Graft Maturation

The maturation and incorporation of ACL substitutes occurs over a period of time and is dependent upon graft placement, tensioning, and whether the tissue is from an allograft source or an autogenous source.[56] These factors are all controlled by the surgeon, but knowledge of the remodeling process is vital to physical therapists as it dictates the rehabilitation of the ACL-reconstructed knee.

The ACL substitutes progress through stages of avascular necrosis, cellular repopulation, collagen remodeling, and maturation.[57] During this process, time-zero graft strength is decreased as the tendinous structure loses some of its characteristic features and gains some ligamentous properties. The process is called ligamentization and was studied by Amiel et al[58] using rabbit patellar tendons. Autologous patellar tendon grafts in the rabbit model increased concentration of type III collagen and glycosaminoglycan molecules to levels similar to those in native ACLs. The adaptations were thought to be due to functional modification resulting from new stresses on the graft.

Ligamentization has been documented to occur in rabbit patella tendons, but these results can not be readily transferred to humans.[55,58] Lane[59] described the changes that occurred in semitendinosus tendon autografts after four years in human subjects. The hamstring tendon autografts had changed from a course, wide crimp pattern to a refined, shorter crimp pattern. Glycosaminoglycans, which are polysaccharides that bind to proteins to form the ground substance in collagen tissues, had almost equivalent concentrations in normal ACLs (8.58 mg/g) and semitendinosus autografts (8.43mg/g). The normal semitendinosus has a glycosaminoglycan concentration of 5.91 mg/g. Cellular composition and collagen structure of the semitendinosus autograft had functionally adapted in order to compensate for the new demands placed on the graft.

Remodeling and maturation of the graft substitutes is characterized by a gradual alteration of the distribution of small and large collagen fibrils.[56] Large collagen fibers of the graft are progressively replaced by small diameter collagen fibrils as the graft becomes a functional scar with a bimodal distribution of small and large fibers. This process results in significant loss of initial strength, and creates a reconstructed ACL that is at its weakest point between six and eight weeks postoperatively.[60] A gradual increase in graft strength occurs as the graft matures from eight weeks until it reaches a maximum at approximately 12 months. Autograft and allograft tissues incur significant losses of tensile strength during incorporation and maturation and no study has demonstrated a complete return of initial tensile strength after remodeling is complete. Over-engineering in graft selection concerning time-zero strength and fixation strength is necessitated by this fact.

The mechanical environment of the graft is affected by graft position, graft tension, and forces on the graft from the rehabilitation protocol.[56] Proper graft position by the surgeon is important to prevent the graft from impinging on the intercondylar notch of the femur. The most common result of poor graft position is a loss of terminal extension due to a cyclops lesion. Chronic graft impingement causes an accumulation of bone and soft tissue around the tibial tunnel. A fibrous nodule called a cyclops lesion forms as a result of the chronic irritation and subsequent accumulation of soft tissue.

Adequate graft tension is required to provide anteroposterior knee stability, but too much tension may adversely affect the biologic incorporation of the graft.[56] Graft tension is greatest at extreme extension and flexion, and ACL tension is least between 30 and 45 degrees of knee flexion. Over-tensioning the graft results in reduced anteroposterior laxity that can cause a restriction of knee range of motion and excess stress to the graft. An over-tensioned graft will limit knee kinematics, but a graft that is too lax will not effectively simulate the function of the ACL. Graft position and tension should allow full range of motion of the knee, yet still allow the graft substitute to limit anterior translation of the tibia on the femur.

The surgeon's goal is to reproduce the position and function of the original ACL to enhance the biologic incorporation of the new graft. Rehabilitation specialists need to be aware of the time frames of biological incorporation as they progressively expose the graft to larger forces.

It is the role of the physical therapist to limit anterior tibial translation forces while enhancing return of normal knee kinematics and muscular strength.

Anterior Drawer Force in Rehabilitation

As previously mentioned, the primary function of the ACL is to restrict anterior tibial translation. The concern with any ACL substitute is whether it will tolerate the forces that rehabilitation activities and ADL's will place on it. The previously mentioned concerns such as tensile strength, graft stiffness, graft position, and graft tension are in the hands of the surgeon, but they directly affect the rehabilitation process. Physical therapists must be aware of the strain that is associated with each particular rehabilitation activity in order to individualize the rehabilitation protocol of ACL-reconstructed patients. Hamstring tendons, patellar tendons, and all other graft sources need to be protected from excessive anterior drawer forces during the first eight weeks when the graft is at its weakest.[60]

Grood et al[61] measured the effect of quadriceps activity on anterior displacement in cadaver knees. Active open chain knee extension was simulated in cadaver knees with transected ACLs. Mean quadriceps force required to maintain zero and 45 degrees of knee flexion were 356 N (80 lbs.) and 178 N, respectively. Adding a seven pound ankle weight almost doubled the amount of quadriceps force needed to maintain full extension. When the knee was extended without an ankle weight from 30 degrees to full extension, anterior displacement increased an average of one millimeter. The same motion with a 31 N (7 lb.) ankle weight produced an average increase in anterior translation of almost four mm at 15 degrees of knee extension. The increased anterior displacement during the last 30 degrees of knee extension demonstrates that the ACL is stressed during this range of motion. A larger increase in anterior translation was evident when quadriceps resistance was increased via an ankle weight. This study indicates that open-chain resistive quadriceps activities expose the ACL to progressively larger anterior drawer forces as full knee extension is approached.

Wilk and Andrews[62] concur with the results of Grood et al. During isokinetic testing, the greatest amount of anterior translation occurred from 30-15 degrees of knee extension. Progressive increases in anterior tibial translation were associated with decreasing test velocity from 300 degrees per second to 60 degrees per second. Anterior tibial translation and ACL strain increased as demand for quadriceps force was increased by reducing the velocity during isokinetic testing.

Rehabilitation specialists need to be aware of the amount of strain that the ACL undergoes due to anterior translation during quadriceps and hamstring muscle contraction states at various angles of knee flexion. Beynnon et al[63,64] has studied ACL strain during rehabilitation exercises in vivo. Eleven subjects with normal ACLs had surgery to implant Hall effect transducers (Microstrain Co., Burlington VT) into their ACLs. Anterior cruciate ligament strain values were then determined for a series of rehabilitation activities. (See Table 4.) Beynnon[63,64] investigated the differences in ACL strain values between four conditions: active flexion and extension with and without ankle weights, isometric quadriceps contractions at various knee flexion angles, isometric hamstring contractions at different knee positions, and simultaneous quadriceps and hamstring muscle contractions at different knee flexion angles.

Table 5. Rank Ordering of Different Rehabilitation Activities Based on Peak Strain Values Developed During Activity. (Modified from Beynnon.[63,64])

Activity	Peak Strain
Isometric Quadriceps @ 15 Degrees (to 30 Nm of Extension Torque)[a]	4.4%
Squat with Sportcord	4.1%
Active Range of Motion with 45 N Weight Boot	3.8%
Lachman Test (150 N Shear Force)	3.7%
Squat without Sportcord	3.4%
Active Range of Motion	2.8%
Co-contraction of Quadriceps & Hamstrings @ 15 Degrees[b]	2.8%
Isometric Quadriceps @ 30 Degrees (to 30 Nm of Extension Torque)[a]	2.7%
Anterior Drawer (150N of Anterior Shear)	1.8%
Isometric Hamstrings @ 15 Degrees[c]	0.6%
Co-contraction of Quadriceps & Hams @ 30 Degrees[b]	0.4%
Passive Range of Motion	0.1%
Isometric Quadriceps 60-90 Degrees (to 30 Nm of Extension Torque)[a]	0.0%
Co-contraction of Quadriceps & Hams @ 60 & 90 Degrees[b]	0.0%
Isometric Hamstrings @ 30, 60, and 90 Degrees (10 Nm of Extension Torque)[c]	0.0%

[a]Isometric quadriceps contraction producing extension torque at the knee joint.
[b]Maximal simultaneous contraction of the quadriceps and hamstrings.
[c]Isometric hamstring contraction producing flexion torque at the knee joint.

The results of Beynnon et al[63,64] have vast implications concerning ACL rehabilitation. Beynnon found that mean ACL strain values during knee flexion and extension with and without a 45 N ankle weight attached to the lower leg varied depending on flexion angle and muscle activity level. The ACL strain values were significantly greater during active motion with a 45 N weight versus active motion without a weight at 10 ($p<.01$) and 20 ($p<.02$) degrees of knee flexion. Strain values were least at 90 degrees of knee flexion and greatest at 10 degrees of extension. No significant difference in ACL strain between the weighted and unweighted conditions were evident at 40, 60, and 90 degrees of knee flexion. The increased demand for quadriceps function associated with application of weights during knee extension and flexion increased ACL strain values and shifted the position that the ACL is unstrained to a position of greater flexion. ACL strain values produced by isometric quadriceps contraction of 30 N-m of force were significantly greater ($p<.01$) at 15 and 30 degrees of knee flexion as compared to 60 and 90 degrees. Strain values were significantly greater at 15 degrees than those at 30 degrees for isometric quadriceps contractions.

For isometric hamstring contractions, ACL strain values produced by 10 N-m of knee flexor torque were not significantly different at 15, 30, 60, or 90 degrees.[63,64] The ACL remained, on average, unstrained or very low at all flexion angles. Simultaneous contraction of the quadriceps and hamstrings, which occurs during closed-chain activities, produced ACL strain values that varied depending on knee flexion angles.
Strain values at 15 and 30 degrees of knee flexion were significantly greater than those at 60 and 90 degrees ($p=.004$). Maximal co-contraction of the quadriceps and hamstrings at 15 degrees of knee flexion produced significantly greater strain values than those at 30, 60, and 90 degrees.

Beynnon[63,64] documented the effect of knee position and muscle activity on ACL strain biomechanics. The data benefit physical therapists that are interested in controlling the amount of ACL strain that their rehabilitation protocol produces. A physical therapist can not control the initial tensile strength, stiffness, or fixation strength of an ACL substitute, but he or she is in control of the postoperative management of the ACL patient. This includes restoring normal range of motion and recovering strength of the involved thigh musculature in the acute stages, and gradually returning patients to functional activities.

A program based on maximally protecting the graft would include isometric hamstring activities from 15-90 degrees, isometric quadriceps exercise from 60-90 degrees, co-contractions of the quadriceps and hamstrings at 30-90 degrees, and active flexion and extension motion of the leg without weights between 35 and 90 degrees of flexion.[64] Flexion and extension of the leg with a seven pound weight did not strain the ACL from 45 to 90 degrees of knee flexion. Even though it is impossible to prescribe exercise that optimally stresses the ACL without causing permanent elongation to the graft, knee position and muscle activity can be manipulated to manage the amount of strain that a exercise protocol places on an ACL graft. The ideal program would provide adequate strain to the ACL substitute to enhance the ligamentization process while adhering to the principles of graft incorporation.

Aggressive Rehabilitation

The BPTB graft is the preferred replacement in ACL reconstruction because it is easily harvested and procured, can be fixated firmly, can tolerate an aggressive rehabilitation, and can allow return to vigorous activity in two to six months without compromising long term knee stability.[41] There are concerns that the hamstring tendon graft would not withstand the same rapid rehabilitation process and return to activity. Very few studies have investigated the impact of accelerated rehabilitation on hamstring grafts. Bone-patellar tendon-bone enthusiasts believe accelerated rehabilitation is less attractive with STG grafts because hamstring grafts lack bone-to-bone healing in the first six weeks.

Howell and Taylor[41] conducted a study of 41 patients that had ACL reconstruction surgery using a loop of semitendinosus and a loop of gracilis. The patients were exposed to an aggressive, brace-free rehabilitation program with return to unrestricted sports and work at four months. Functional assessment and arthrometric stability measurements were taken at four months, after completion of an accelerated rehabilitation program, and at two years post-ACL reconstruction. The rehabilitation program included continuous passive motion for the first 24-48 hours after the operation and toe-touch weight bearing for three weeks. Patients were walking without crutches at three weeks, and at four weeks the subjects began unrestricted open and closed-chain knee extension. Straight line running was resumed at eight weeks, and patients were returned to unrestricted sports activity and work at four months.

Thirty-seven (90%) of the 41 ACL-reconstructed knees in Howell and Taylor's[41] study were stable and functional after two years. The manual maximum test using the KT-1000 revealed 90% of the treated knees had 2.5 mm or less anterior laxity difference as compared to the uninjured knee. Anterior laxity difference of greater than three mm between the sound and reconstructed knees is considered unstable when using the KT-1000 arthrometer.[65] Ninety-three percent of the patients returned to moderate or strenuous activities two years following the operation. Skiing, tennis, baseball, and volleyball are considered moderate, or level two activities. Pivoting sports such as football, soccer, and basketball are considered strenuous, or level one activities. The grafts were mature enough after four months to stabilize the knees, since return to vigorous activities did not create instability. Knee stability in this study was equal to that reported in two previous studies[66,67] using BPTB grafts. The double-looped STG graft can be used when an accelerated rehabilitation program with early return to strenuous activities is the goal.[41]

Howell and Taylor[41] suggest that their results are due to superior surgical techniques and fixation strengths. The hamstring graft in this study was looped around a fixation post within the tibial tunnel. This allowed the distal end of the graft to be fixed four to five centimeters more proximally than those that are fixed to bone outside of the distal tibial tunnel. The free ends of the graft were fixed proximally using one or two cancellous bone screws and soft tissue washers. Pullout strength of this fixation method has not been determined, but studies have demonstrated that hamstring grafts can be fixated as securely as BPTB grafts.[53,54] Adequate fixation of hamstring grafts can allow for accelerated rehabilitation and early return to vigorous activities.

Long-term Outcomes

A common misconception concerning hamstring tendon grafts is that the graft will stretch out over time as it is exposed to repeated submaximal stresses from rehabilitation and activities of daily living.[68] This belief exists due to the early use of single or double-stranded grafts and poor surgical techniques. The hamstring graft has evolved to primarily include quadruple-stranded or double-looped graft types. Research has shown that these grafts produce tensile strength that is superior to the central one-third BPTB graft.

Comparisons of the outcomes of ACL reconstructions using hamstring and patellar tendon grafts are difficult to make.[4] Factors such as surgical technique, postoperative rehabilitation program and compliance, time to follow-up evaluation, and lack of standardized procedures to evaluate stability and function can create bias in a study. Surgical techniques, graft types, and rehabilitation principles have evolved so quickly that only a few random studies with long-term follow-up exist.

Clinical studies using quadruple semitendinosus or double-looped STG have demonstrated results comparable with those of BPTB grafts.[43,44,69] Marder[43] and Aglietti[44] conducted random studies comparing the long-term outcomes of double-looped STG grafts with BPTB grafts that underwent similar rehabilitation consisting of immediate passive extension and early knee motion. The authors agreed that no significant differences existed between the two types of grafts. The STG graft produced less stability, though not significant, but was associated with less extension loss and patellar problems. Marder and Aglietti concluded that, with their surgical technique, the STG graft should be implemented in older patients with lesser physical demands, in acute knees with isolated ACL tears, in patients with preexisting patellofemoral problems, and in patients with failed patellar tendon grafts.

Maeda et al[69] evaluated the long-term outcome of the quadruple-stranded hamstring grafts using the Rosenberg technique. Forty-one knees were reconstructed and evaluated between two and four years postoperatively. The average anterior laxity difference between the involved knees was 1.5 +/- 2.3 mm. Arthrometric measurements revealed

71% of the subjects had less than three mm of anterior laxity at 200 N of force. These laxity results are better than the results of Marder[43] (1.7 mm) using 89 N of force.

Brown et al[30] favor hamstring tendon grafts in patients with a history of patellar pain, patellar tendinitis, patellar subluxation, and patients with small patellar tendon widths. Patients with occupations that require significant amounts of kneeling, crawling, or squatting would benefit from the hamstring procedure because it is associated with less donor site pain. Hamstring grafts have better results in acute knees with isolated ACL tears and chronic ACL-deficient knees without generalized patholaxity.[1] Even though the BPTB ACL reconstruction is often termed the "gold standard," recent prospective studies[43,44] have demonstrated equivalent outcomes when patellar tendon grafts were compared to double-looped hamstring tendon ACL reconstructions.

CHAPTER VI

SUMMARY

Arthroscopically-assisted anterior cruciate ligament reconstruction using hamstring tendons is no longer considered a new technique, and it has recently gained widespread acceptance.[30,41,68] The purpose of this review was to investigate the misconceptions surrounding the hamstring tendon graft and to document that equal or better long-term results can be achieved with hamstring grafts when compared to BPTB grafts. Evidence has been provided to refute the concerns that still persist regarding the use of hamstring tendons as autologous ACL substitutes. Research has shown that hamstring graft misconceptions such as inferior mechanical strength, residual hamstring strength deficit, fixation strength deficit, stretching of the graft construct over time, and an inability to tolerate the strain of accelerated rehabilitation protocols are not justified. Although the use of the patellar tendon in ACL reconstructions has often been considered the "gold standard," reconstruction of the ACL-deficient knee using hamstring tendons has produced equal or better results than reconstructions with autogenous patellar tendons.[41,43,44,68,69]

Thomas Rosenberg is a leading proponent in the use of autogenous semitendinosus tendons as ACL substitutes.[69] He suggested, in 1989, that tripled or quadrupled semitendinosus tendons could overcome the disadvantages associated with BPTB grafts and compensate for the mechanical inferiority of double and single limb semitendinosus tendon grafts. Rosenberg[68] believes that his surgical technique, fixation method, and hamstring graft replacement produces superior initial tensile strength, equivalent fixation strength, and biologic incorporation that exceeds that of the BPTB graft. He is confident that hamstring tendons provide enough initial tensile and fixation strength to allow accelerated rehabilitation. Howell and Taylor[41] demonstrated that a double-looped STG hamstring graft is a viable option when aggressive rehabilitation of the knee and return to sports in four to six months is desired.

This review has provided significant evidence to justify the use of hamstring grafts as autologous ACL substitutes for ACL-deficient knees, but the debate over graft selection is currently not resolved. The best graft can only be determined by long-term clinical studies that assess stability and functional outcomes using specific grafts, methods of fixation, and rehabilitation protocols. More long-term studies that compare and isolate specific graft types, surgical techniques, and rehabilitation protocols need to be conducted to determine the ideal ACL substitute. The hamstring tendons have shown that they can replace the normal ACL and provide equal or better long-term results when compared to the commonly used BPTB graft.

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